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Morphological characterisation of reef types in Torres Strait and an assessment of their carbonate production

Abstract

Coral reefs represent major accumulations of calcium carbonate (CaCO₃). The particularly labyrinthine network of reefs in Torres Strait, north of the Great Barrier Reef (GBR), has been examined in order to estimate their gross CaCO₃ productivity. The approach involved a two-step procedure, first characterising and classifying the morphology of reefs based on a classification scheme widely employed on the GBR and then estimating gross CaCO₃ productivity rates across the region using a regional census-based approach. This was undertaken by independently verifying published rates of coral reef community gross production for use in Torres Strait, based on site-specific ecological and morphological data. A total of 606 reef platforms were mapped and classified using classification trees. Despite the complexity of the maze of reefs in Torres Strait, there are broad morphological similarities with reefs in the GBR. The spatial distribution and dimensions of reef types across both regions are underpinned by similar geological processes, sea-level history in the Holocene and exposure to the same wind/wave energetic regime, resulting in comparable geomorphic zonation. However, the presence of strong tidal currents flowing through Torres Strait and the relatively shallow and narrow dimensions of the shelf exert a control on local morphology and spatial distribution of the reef platforms. A total amount of 8.7 million tonnes of CaCO₃ per year, at an average rate of 3.7 kg CaCO₃ m⁻² yr⁻¹ (G), were estimated for the studied area. Extrapolated production rates based on detailed and regional census-based approaches for geomorphic zones across Torres Strait were comparable to those reported elsewhere, particularly values for the GBR based on alkalinity-reduction methods. However, differences in mapping methodologies and the impact of reduced calcification due to global trends in coral reef ecological decline and changing oceanic physical conditions warrant further research. The novel method proposed in this study to characterise the geomorphology of reef types based on classification trees provides an objective and repeatable data-driven approach that combined with regional census-based approaches has the potential to be adapted and transferred to different coral reef regions, depicting a more accurate picture of interactions between reef ecology and geomorphology.

Keywords

carbonate, production, morphological, characterisation, reef, types, marine, torres, geology, strait, assessment, their, GeoQuest

Disciplines

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Morphological characterisation of reef types in Torres Strait and an assessment of their carbonate production

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Abstract

Coral reefs represent major accumulations of calcium carbonate (CaCO_3). The particularly labyrinthine network of reefs in Torres Strait, north of the Great Barrier Reef (GBR), has been examined in order to estimate their gross CaCO_3 productivity. The approach involved a two-step procedure, first characterising and classifying the morphology of reefs based on a classification scheme widely employed on the GBR and then estimating gross CaCO_3 productivity rates across the region using a regional census-based approach. This was undertaken by independently verifying published rates of coral reef community gross production for use in Torres Strait, based on site-specific ecological and morphological data. A total of 606 reef platform were mapped and classified using classification trees. Despite the complexity of the maze of reefs in Torres Strait, there are broad morphological similarities with reefs in the GBR. The spatial distribution and dimensions of reef types across both regions are underpinned by similar geological processes, sea-level history in the Holocene and exposure to the same wind/wave energetic regime, resulting in comparable geomorphic zonation. However, the presence of strong tidal currents flowing through Torres Strait and the relatively shallow and narrow dimensions of the shelf exert a control on local morphology and spatial distribution of the reef platforms. A total amount of 8.7 million tonnes of CaCO_3 per year, at an average rate of $3.7 \text{ kg } \text{CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ (G), were estimated for the studied area. Extrapolated production rates based on detailed and regional census-based approaches for geomorphic zones across Torres Strait were comparable to those reported elsewhere, particularly values for the GBR based on alkalinity-reduction methods. However, differences in mapping methodologies and the impact of reduced calcification due to global trends in coral reef ecological decline and changing oceanic physical conditions warrant further research. The novel method proposed in this study to characterise the geomorphology of reef types based on classification trees provides an objective and repeatable data-driven approach that combined with regional census-based approaches has the potential to be adapted and transferred to different coral reef regions, depicting a more accurate picture of interactions between reef ecology and geomorphology.

Keywords: carbonate production; Landsat ETM+; classification trees; coral reefs; geomorphology

1 Introduction

It is important to understand the interactions between atmospheric CO₂ and the carbonate budget of reefs (Berger, 1982), particularly in the context of the accelerated increase of CO₂ concentrations due to human-induced emissions and its implications in relation to the future of reef systems (Veron et al., 2009). Coral reefs sequester carbon in the form of calcium carbonate (CaCO₃) over geological time scales. The capacity of corals to deposit CaCO₃ is controlled by the saturation state of CaCO₃ in seawater (Ω). As concentrations of atmospheric CO₂ increase, Ω decreases and so does coral calcification (Kleypas et al., 1999). Over shorter historical time scales (10-100s years), as the surface water geochemistry is modified, coral reef systems can release CO₂ and act as net contributors of CO₂ to the atmosphere (Ware et al., 1991).

A coral reef can be considered as a “carbonate factory” involving processes of CaCO₃ production and loss (Pomar and Hallock, 2008). From a geomorphic perspective, the balance represents net CaCO₃ accumulation, with a positive budget implying reef accretion, while processes such as physical abrasion, bioerosion and dissolution represent negative contributions to the budget. The carbonate budget approach is an appropriate framework that allows analysis of the various components of reef function and structure at appropriate spatial scales (e.g. within a whole-reef or between reefs) over time, effectively linking ecological and morphological changes (Buddemeier and Smith, 1988; Perry et al., 2008). However, current understanding of ecomorphodynamic interactions remain poorly resolved, with anticipated shifts in ecological processes due to climate change, adjustments in sediment production and transport that will affect associated landforms such as reef islands, and further implications for reef morphology (Perry et al., 2011).

Direct estimates of reef metabolism have shown that the intricate cycling and dynamics of CaCO₃ can result in intra-reef zones acting simultaneously as carbonate sources and sinks within coral reef systems (Gattuso et al., 1999; Kinsey and Davies, 1979; Yates and Halley, 2003). Such measurements, however, are complicated and prohibitively costly across large reef systems (Zhang et al., 2012). Maps of the geomorphic zones which characterise coral reefs can also be used to provide an indication of the distribution, patterns and extent of different coral reef biological communities and to estimate reef growth, productivity or coral health across regions (Andréfouët et al., 2006; Hamylton et al., 2012). Scaling-up coral reef gross production and calcification rates has been undertaken at different spatial scales and levels of generalization by linearly extrapolating metabolism rates based on the areal extent

of geomorphic and benthic community zones, from individual reef platforms (Ahmad and Neil, 1994; Ryan et al., 2001), to synoptic coral reef regions (Andréfouët and Payri, 2000; Brock et al., 2006; Kinsey and Hopley, 1991; Moses et al., 2009), to global estimates (Vecsei, 2004).

The reefs of Torres Strait, between Cape York Peninsula and Papua New Guinea, comprise a particularly complex maze, termed the “labyrinth” by Captain James Cook, which extends across the continental shelf beyond the northern end of the Great Barrier Reef (GBR) (Fig. 1). They have continued to pose an obstacle to mariners since the skilled Galician navigator, Luis Vaz de Torres (after whom the strait is named), commanded the first known voyage through the passage in 1606, taking two months to battle the strong winds and tidal currents. As Hopley et al. (2007) noted, the reefs in Torres Strait still remain inadequately studied and mostly uncharted at a detailed level, away from major shipping routes, despite being adjacent to the well-studied GBR. This represents a gap in understanding regional spatial patterns of coral reef geomorphology and evolution, which are important for the long-term management of these ecosystems.

In this paper we describe the morphology of reefs in Torres Strait and estimate their gross CaCO_3 productivity based on detailed intra-reef geomorphological mapping in conjunction with comprehensive information about links between geomorphology and biological communities, and published metabolic rates. Estimates of the carbonate budget for an emergent reef in Torres Strait are described, extending the earlier studies of that reef (Hart and Kench, 2007). CaCO_3 productivity is extrapolated across the entire region adopting a regional census based approach (Vecsei, 2001, 2004) and building on methods to scale-up the gross CaCO_3 production for the complete GBR reef system (Kinsey and Hopley, 1991) based on the geomorphic characteristics of these reef types (Hopley, 1982; Hopley et al., 2007).

2 Regional Setting

Torres Strait lies between Cape York Peninsula, the northernmost point of mainland Australia, and the south coast of Papua New Guinea. It formed a land bridge between these two landmasses during the Late Pleistocene, but became submerged as sea level rose and flooded the underlying Oriomo Ridge. The Strait contains a discontinuous chain of granitic islands to the west (e.g. Thursday Island) and younger volcanic islands fringed by coral reefs to the east (e.g. Murray Island) (Fig. 1).

The central section comprises a maze of scattered coral reef platforms and submerged *Halimeda* banks (Heap and Scaffi, 2008). Considerable reef growth was initiated over the mostly shallow shelf (15-30m) as it was flooded by the sea. It is generally considered that the land bridge was severed when the sea rose beyond 12 m below present sea level. Platform reefs are common in the central Torres Strait region, rising abruptly from shallow depths. They are Holocene in age and appear to be founded on the remnants of earlier Pleistocene reefs and other non-reefal topographic remnants as shallow as 6 m below sea level (Woodroffe et al., 2000).

There are geomorphological similarities between coral reefs in Torres Strait and those on the GBR as both reef tracts have experienced a similar sea-level history during the Holocene. Hopley (1982) proposed a classification of coral reef types for the GBR based on interpretation of intra-reef geomorphic zones from large-scale aerial photography. It was complemented by a thorough analysis of surface and subsurface sediments, stratigraphy and radiocarbon dating and it remains central to description of GBR reefs, 25 years later (Hopley et al. 2007). The different reef types were interpreted to represent progressive evolutionary stages in platform development, from juvenile reefs (submerged and patches), through mature (crescentic and lagoonal), to senile reefs (planar). Additionally, ribbon and fringing reef types are also recognized (Fig. 5.6 and Table 5.3 in Hopley et al., 2007).

Preliminary geomorphological and geochronological studies indicate that several Torres Strait reefs have grown up to, and their upward growth was constrained by, a sea level slightly above present around 5,000 years ago. Coring on Warraber (Sue) reef (Fig. 1) showed that the reef platform has built laterally since that time with much of the former reef top now emergent as a largely barren sandy reef flat exposed at low tide (Woodroffe et al., 2000). This reef platform is similar to planar reefs in the GBR in regards to the proportion of intra-reef geomorphic zones, although it has evidently not evolved through the infill of a lagoonal reef as implied in Hopley's model.

Additionally, reef platforms such as the extensive Warrior reefs (Fig. 1) are characterised by an incomplete reef rim best developed on the eastern windward margin and with sheltered backreef environments that remain beneath water at all stages of the tide. These are comparable to crescentic reef types. Moreover, numerous shelf-edge and dissected reefs occurring on the eastern edge of Torres Strait are comparable to the outer ribbon reefs of the northern GBR (Veron, 1978).

Conversely, there are several distinctive reef platforms in Torres Strait. For example, the Cumberland reef complex (Fig. 1) is a network of relatively large reefs (~50 km²) with a

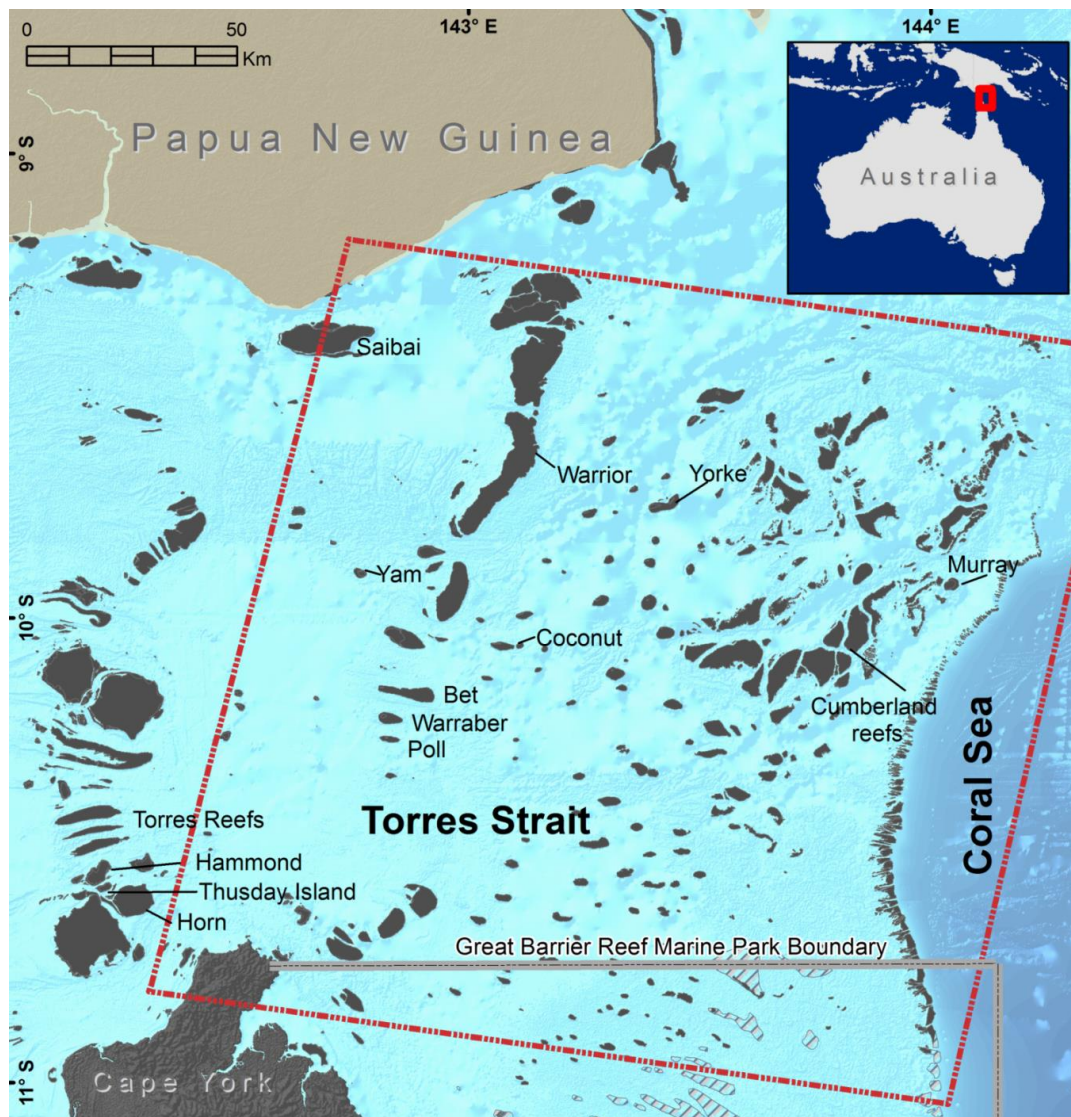


Fig. 1: Torres Strait, showing location of reefs mentioned in text and extent of Landsat ETM+ images (red outline). Shaded relief is based on bathymetry by Daniell (2008).

pattern that resembles the smaller deltaic reefs in the GBR. Evidence suggests that such reef platforms have grown from deep shelf valley systems incised by strong tidal currents (Harris et al., 2005). The strong tidal currents funnelling from the Coral Sea into the Gulf of Carpentaria (Saint-Cast, 2008) have also been attributed to the distinctive east-west orientation of many reef platforms in Torres Strait (Brander et al., 2004).

Jones (1995) related the elongated morphology of Torres Reefs (several distinct linear west-east reefs just north of Hammond Island, Fig. 1) to the progressive lateral colonisation of reef patches over sediment transported and accumulated by strong tidal currents of up to 2 ms^{-1} . Analysis of seismic profiles showed that the intertidal reef “tail-end” was composed of reef patches infilled with unconsolidated sediment, which was explained as a consequence of

the stepwise growth of the platform margin. Woodroffe et al. (2000) came to similar conclusions based on coring and dating of the linear coral-covered features parallel to the modern reef crest, considered former reef crests, on the elongated Warraber reef platform.

3 Methods

Our study involved two steps. The first step classified reef platform types in Torres Strait based on Hopley's classification scheme. The second step consisted of scaling-up gross CaCO_3 production from individual reef types to a regional scale across Torres Strait. This was undertaken by adapting published rates of coral reef community gross production for use in Torres Strait, based on site-specific ecological and morphological data. Gross production rates adapted to Torres Strait were then linked to mapped geomorphic zones following the approach pioneered by Kinsey and Hopley's (1991).

3.1 Coral reef types

Geospatial procedures for classifying coral reef geomorphology lag behind terrestrial applications where semi-automated geomorphological mapping approaches are gradually replacing conventional manual interpretations due to improved geospatial techniques and increasing availability of high-quality digital elevation data (Drăguț and Eisank, 2012; Zieger et al., 2009). Classification trees have been successfully used in geomorphological research because of their relative simplicity for the exploration of complex datasets and their predictive capability (Luoto and Hjort, 2005). Currently, only sparse data, such as detailed bathymetry and ground reference, is available over complex reefs. A combination of remotely sensed data, geospatial techniques and rule-inductive classification algorithms was used in this study to classify reefs in Torres Strait (Fig. 2). The target category, reef type, was predicted based on attributes that included physical and morphological variables associated with each reef platform. Six reef type categories, based on Hopley's classification scheme, were adopted in Torres Strait due to broad similarities in the proportion of geomorphic zones between these reefs and the ones in the GBR (see Fig. 7). A training dataset consisting of one third of the samples per reef type across Torres Strait ($N=206$) were labelled based on visual interpretation of pan-sharpened Landsat ETM+ images (15 m spatial resolution) acquired 6 July 2001 and 23 March 2003, and oblique digital photos and video taken from a low-flying fixed-wing airplane during September 2007 (Fig. 3).

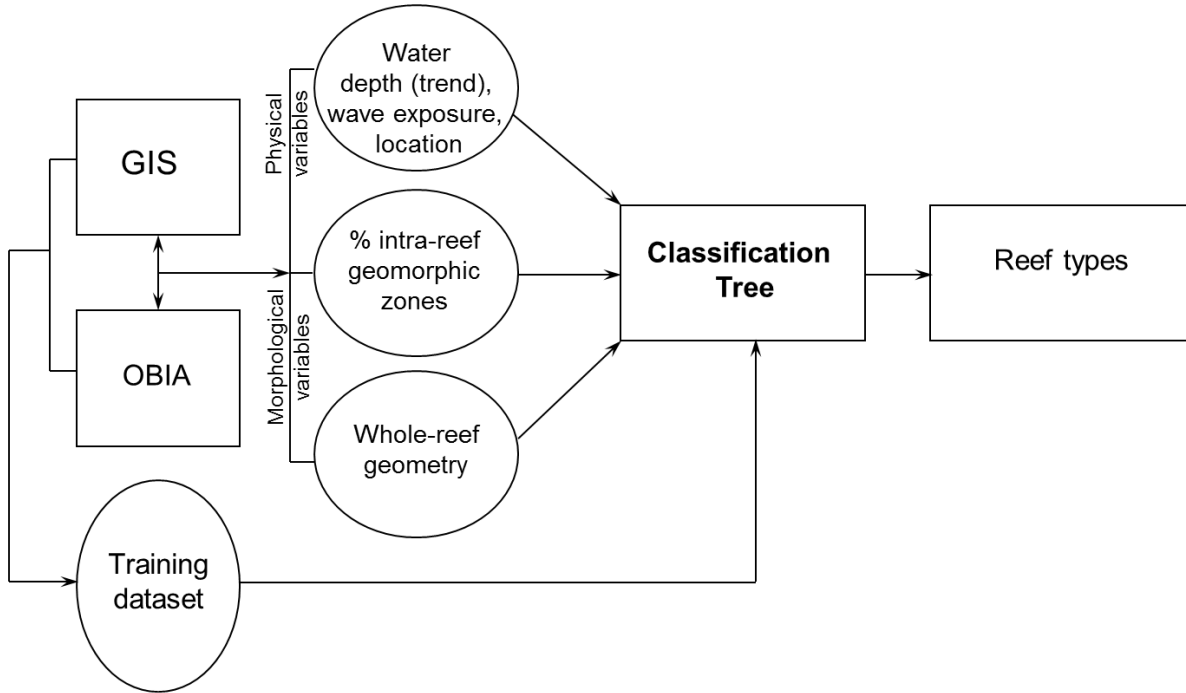


Fig. 2: Graphical overview of procedures to classify reef types in Torres Strait using classification trees within a geospatial framework.

Physical or environmental variables that would be required to explain the geomorphology of specific reefs, such as depth to antecedent Pleistocene foundations or hydrodynamic measurements are generally unavailable or imprecise for the study area. Three proxies were used instead: water depth, wave exposure and geographic location. An assumption was made that the general bathymetric trend followed the progressive west to east cross-shelf deepening in Pleistocene foundation, as noted by Hopley et al. (2007). A global trend (3rd order polynomial) was fitted to the 110 m resolution digital elevation model elaborated by Daniell (2008).

Direct wave measurements on coral reefs are usually limited temporally and spatially, particularly around the energetic reef crest (Brander et al., 2004). In this context, using a spatially-explicit wave exposure analytical model (e.g. Puotinen, 2005; Tolvanen and Suominen, 2005) offers a first-approximation alternative to the more complex spectral and phase-resolving numerical wave models that require precise depth and wave datasets for calibration and validation (Hamm et al., 1993). Wave exposure is calculated as a function of the uninterrupted fetch distance for specified points. The average wave exposure acting on

each reef platform in Torres Strait was approximated using the GREMO tool (Pepper and Puotinen, 2009). Sites were defined every 250 m around reef outlines, and fetch lines were constructed for all directions at aspect increments of 22.5° around each reef-margin site. Maximum fetch distance was constrained to 650 km, as this length corresponds to the maximum fetch length for fully arisen seas at gale force winds (defined by the Australian Bureau of Meteorology as 17.5 ms⁻¹), and fetch values were normalized using the maximum sum of fetch lines for the 16 directions (10,400 km). Maximum, minimum and mean values of multidirectional wave energy exposure indices were calculated. In addition to wave exposure indices, geographic location (latitude and longitude) were used as a third physical variable to account for latitudinal and across-shelf longitudinal spatial gradients of physical processes.

Two groups of morphological variables were used. The first group consisted of the proportions of mapped intra-reef geomorphic zones (Leon and Woodroffe, 2011) for each reef platform. The second group of morphological variables consisted of whole-reef platform geometric variables commonly used in landscape ecology such as compactness, elliptical fit and roundness (McGarigal and Marks, 1995).

The data mining software Weka 3.6 (Witten and Frank, 2005) was used to run decision trees based on the J4.8 decision tree learner, Weka's implementation of the popular C4.5 algorithm (Quinlan, 1993). Trees were run for different combinations of variables. A 10-fold cross-validation was used to select the best tree based on the size of the tree, misclassification rates and the kappa index.

3.2 Coral reef CaCO₃ production

Coral reef metabolism is controlled by the balance between respiration and photosynthetic carbon fixation. The gross production (G) is the amount of CaCO₃ produced per unit area over time (kg CaCO₃ m⁻² yr⁻¹), while net production is the amount of CaCO₃ retained by the reef system after removal by biological, physical and chemical erosion (Chave et al., 1972). Four different techniques have been used to quantify carbonate production on reefs: hydrochemistry, census-based, geological evidence and numerical modelling. Each technique is best suited to measure different productivity categories and is limited due to considerations relating to logistics, precision and scale (Perry et al., 2012; Vecsei, 2004). Nonetheless, results from these approaches are comparable and, in combination, enable development of theoretical models of reef development in the Holocene (Hopley, 1982). In

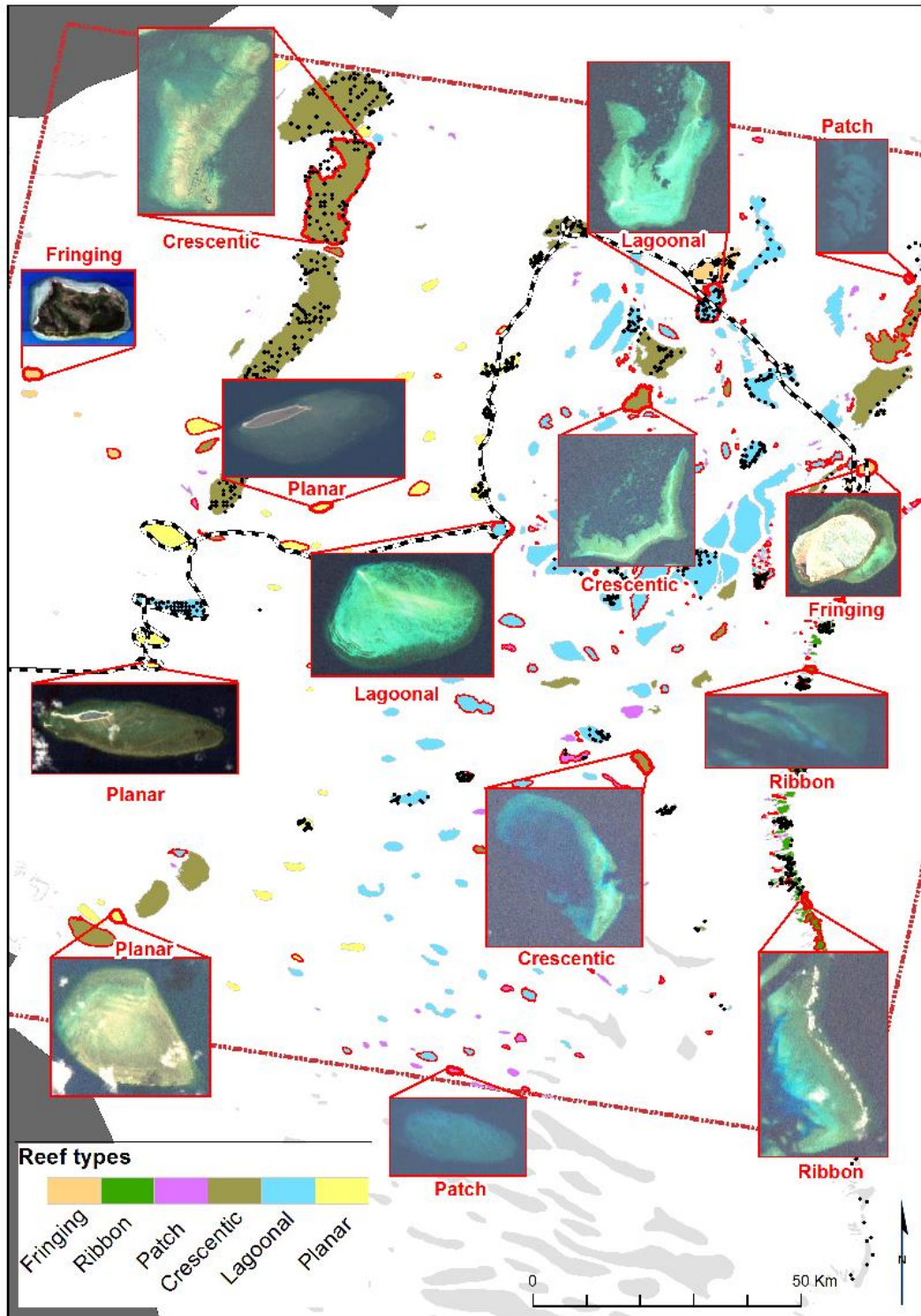


Fig. 3: Reef types in Torres Strait classified using classification tree. Training dataset used for classification is shown (reefs outlined in red) with selected examples of labelled reef types. Reference data used across the study area included a low-altitude flight survey (black and white dashed line) and a reef habitat mapping survey undertaken by Long et al. (2007) (black dots). Unclassified reefs (grey shade) within the extent of Landsat ETM+ image (thick dotted red outline) were covered with clouds.

order to estimate gross productivity for Torres Strait, published rates based on hydrochemistry studies were independently verified and complemented using a regional census-based approach for different reef types across Torres Strait.

Hydrochemistry-derived gross CaCO₃ production rates

CaCO₃ production rates were determined for a range of coral reef communities by Kinsey and co-workers using alkalinity-anomaly methods during the 1970s and 1980s (for a comprehensive review see Kinsey 1985), and have been widely used since. This method measures inorganic gain, incorporating early dissolution, per unit area over time and is averaged to the long-term net growth of the reefal structure, expressed as the community metabolic performance or gross reef production (G in kg CaCO₃ m⁻² yr⁻¹). Results suggested that G values measured at whole-reef and intra-reef reef community spatial scales were comparable across geographical gradients and between different reef tracts, despite large variability in coral assemblages (Chave et al., 1972; Kinsey, 1985; Smith and Kinsey, 1976). More recent studies have also reported comparable G values to those measured in the 1970s (e.g. Brock et al., 2006; Gattuso et al., 1997; Yates and Halley, 2003), although empirical studies suggest calcification is reducing as a result of increase in sea surface temperature and partial pressure of CO₂ (Silverman et al., 2009).

Kinsey and Hopley (1991) derived generalized gross production rates (G values) for intra-reef geomorphic zones in the GBR based on a combination of 3 absolute modes defined by Kinsey (1979). These modes spanned from 100% hard coral/algal coverage (10 G), to 100% sand and rubble cover (0.5 G), to 100% algal pavement (4 G). Attenuation by depth (e.g. > 10 m) and exposure to energy were also incorporated. For example, deep reef shoals or coral patches entirely covered by live coral were assigned a value of 2 G based on the diversity and depth of such systems (Fig. 4).

Productivity of leeward or backreef environments exposed to less wave energy, such as deep lagoons, is generally as low as 0.8 G (Smith and Kinsey, 1976), but it has been estimated to vary from 0.5 to 1.5 G (Davies and Marshall, 1979). Additionally, lagoonal CaCO₃ accretion has been observed in the GBR at a rate equal to, or greater than, the maximum gross production measured at windward forereef zones during prevailing SE wind due to removal and transport of reefal material (Davies, 1977). Consequently, a value of 2 G was assigned to deep lagoon zones and other leeward environments as these usually contain scattered small reef patches covered with live coral (e.g. Flood and Scoffin, 1978).

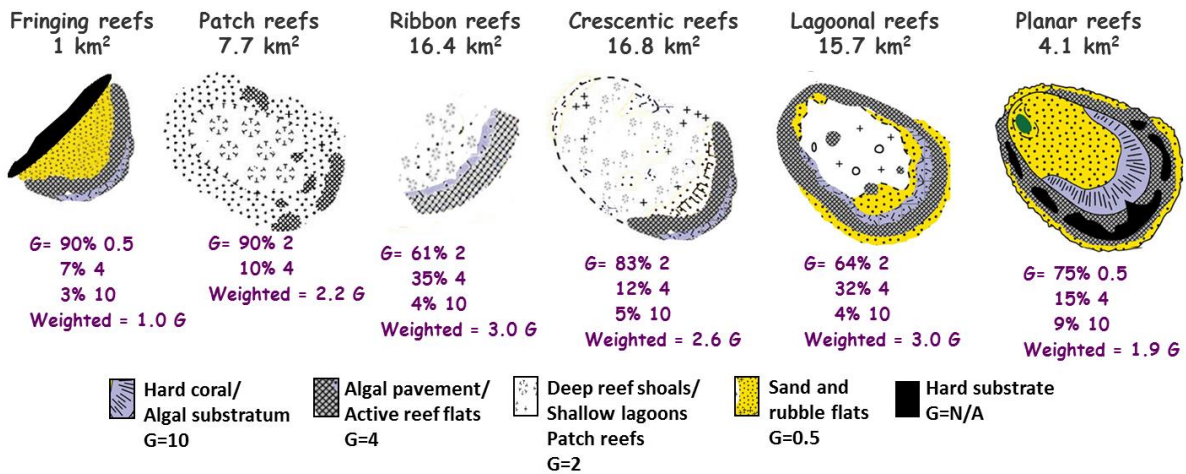


Fig. 4: The average size (km²), schematic representation (not drawn to scale) of geomorphic zones (%) and proportional/weighted gross CaCO_3 production rates (G) for each of the 6 reef types for the GBR based on Hopley's classification scheme (after Kinsey and Hopley, 1991).

Regional census-based gross CaCO_3 production rates

The relationships between ecological cover, gross CaCO_3 production and geomorphology of reefs in Torres Strait were investigated and gross productivity scaled-up using a regional census-based method. This method, as proposed by Vecsei (2001), is a modification of the traditional census-based approach which relies in measured abundance and growth rates of carbonate producing organisms (Chave et al., 1972; Harney and Fletcher, 2003). A regional census-based approach uses regionally averaged coral cover and growth data derived from published figures and assumes that gross production is an additive process across spatial scales (Andréfouët and Payri, 2000). Here, we used generalized census-based gross productivity estimates for two typical reef platforms and extrapolated rates across the Torres Strait region in order to verify and complement estimates derived from hydrochemical methods.

Warraber reef is a typical emergent reef platform in Torres Strait. The composition, abundance and spatial distribution of benthic coverage across this reef flat was recorded on site-specific surveys undertaken by Hart (2003) and summarized in Hart and Kench (2007). Ten eco-geomorphic zones were identified based on the percentage of primary and secondary calcifying organisms (Fig. 5 and Table 1). The average and standard deviation rates of gross CaCO_3 production were estimated for each mapped zone (Table 2). A total of $17,399 \pm 18,618 \text{ t CaCO}_3 \text{ year}^{-1}$ gross production, averaging a production rate of 1.66 G , was derived for the reef flat based on the census approach, which was comparable to estimates based on

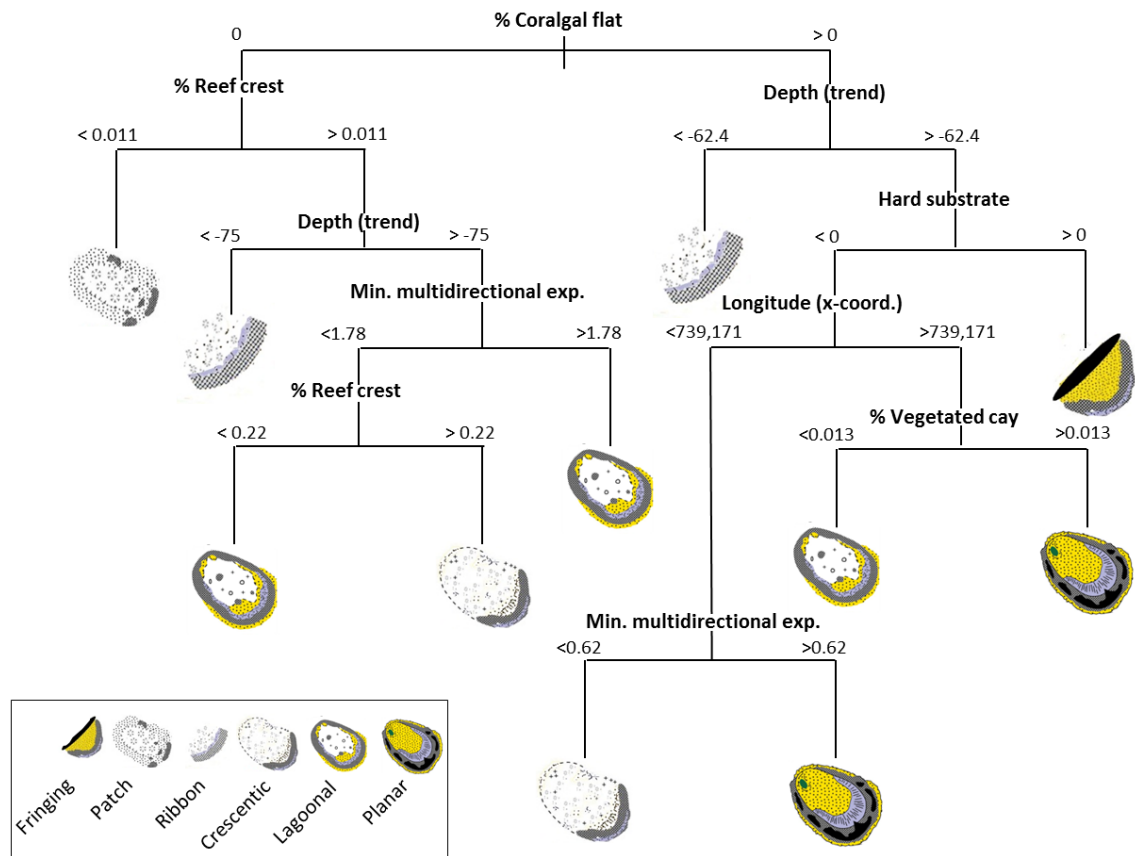


Fig. 5: Warraber reef, showing areas exposed to more frequent SE waves and least frequent NW waves. Overlaid are eco-geomorphic zones as mapped by Hart (2003): 1) Sandy reef flat with molluscs, 2) Sandy reef flat with algae, 3) Sandy reef flat with coral, 4) E raised algal rim, 5) Fine sand reef flat, 6) W mixed coral, 7) W raised algal rim, 8) Dense branching coral, 9) E mixed coral. Coral cover and composition on reef flat and forereef, as characterised from surveys undertaken by Hart (2003) and Skewes (1997), respectively.

alkalinity-reduction techniques. Hart and Kench (2007) concluded that this lower productivity rate estimate, compared to the 4 G reported for other reef flats, resulted from the limited coverage of primary producers due to the extent of an emerged supratidal sanded reef flat.

The carbonate budget for the reef top, estimated by Hart and Kench (2007), has been extended in this study to include the productive forereef zone. Gross productivity around the forereef was estimated based on the spatial distribution of coral composition and coverage. The percentage coverage of hard substrate, sand, live coral and algae was described during an intensive lobster survey undertaken by Skewes (1997). Data was collected at regular points around the reef crest by divers. A total of 36 line-transects extending approximately 50-meter from the reef crest were surveyed with observations recorded every 5 meters. Observations

335 Table 1: Estimated calcification rates for main carbonate producing organisms derived from review of published data
 336 (Modified from Table 2, Hart and Kench 2007)

Organism	Best-estimate calcification rate (G) with minimum-maximum range in brackets	Adjustment factor	Percentage of area occupied by carbonate producers (%)
Coralline algae	1.87 (1.5-2.5)	Multiplied by square of rugosity	47
Coral massive	16.16 (7.68-24.64)		26
Coral-foliose/encrusting/mushroom	17 (3.0-31)		1
Coral ramose- <i>Acropora</i>	19.24 (10.82-27.67)	Multiplied by effective cover factor of 0.25	4
Coral ramose-other	1.39 (0.77-2.02)	Multiplied by a branch extension factor of 0.4	12
<i>Halimeda</i>	1.07 (0.4-1.67)		6
Foraminifera	0.12 (0.03-0.23)	Multiplied by a factor between 0-3 depending on density	1
Molluscs	0.1 (0.01-0.2)	Multiplied by a factor between 0-3 depending on density	3

were grouped into major coral growth forms (branching, plate, massive) and the coralline algae *Halimeda* in order to be comparable with Hart's classes. Data were stratified by depth and analysed as a function of wave exposure (Leon, 2010) (Fig. 5). The forereef around Warraber is mostly composed of branching and massive coral types with coverage ranging from 70-100% in the less exposed western sector to 10-60% in the most exposed eastern sector (Leon, 2010). Approximately 2,033 t CaCO₃ year⁻¹ of gross productivity, equalling to a rate of 7.4 G, was estimated based on the 360 diver observations and calcification rates defined by Hart and Kench (2007). This estimated productivity on the forereef, in

Table 2: Estimated average gross carbonate production rates (G) and standard deviation (std) across eco-geomorphic zones of Warraber reef flat mapped by Hart and Kench (2007)

Zone	Average G	std
1. Sandy reef flat with molluscs	0.15	0.12
2. Sandy reef flat with algae	0.16	0.19
3. Sandy reef flat with coral	3.16	3.93
4. E raised algal rim	1.08	0.82
5. Fine sand reef flat	0.07	0.11
6. Mixed coral	4.00	1.34
7. W raised algal rim	0.82	0.23
8. Dense branching coral	1.05	0.30
9. Mixed coral	1.76	0.89
Total reef flat	1.66	1.78

combination with Hart's reef top estimate, adds up to an average productivity rate of 1.81 G across the emergent platform of Warraber reef.

Bet reef, to the north of Warraber reef (Fig. 1), is a typical submerged reef platform in Torres Strait characterised by a shallow but mostly submerged reef flat/backreef with widespread occurrence of sand aprons. The percentage coverage of hard substrate, sand, live coral and algae was described during a reef habitat mapping survey undertaken in 1997 (Long et al., 1997). The ecological survey was carried out by divers along 20 m transect lines at 43 and 13 random sites on the reef top and forereef, respectively. The ecological data was grouped into the same categories used by Hart and Skewes and summarized around the platform (Leon, 2010). The data, although not as extensive as the surveys on Warraber, indicate that fast growing branching corals are distributed towards the inner reef flat along the relatively deeper areas adjacent to the windward reef crest and along the leeward backreef zone. An average 85% coral coverage, mostly branching types, was recorded on the leeward reef slopes of the platform, with lower coverage on the windward forereef by plate and massive coral types (Leon, 2010). Assuming the growth rates for coral and secondary producers defined for Warraber reef, a gross $67,580 \text{ t CaCO}_3 \text{ year}^{-1}$ was estimated to be produced on the reef top and approximately $20,587 \text{ t CaCO}_3 \text{ year}^{-1}$ around the forereef. This results in an average production rate of 3.14 G for the complete Bet reef platform.

In addition to estimates of gross productivity for these two typical reef platforms in Torres Strait, productivity rates were generalized for geomorphic zones based on the survey undertaken by Long et al. (1997) covering a total of 1,644 sites across the region (Fig. 3).

Table 3: CaCO₃ production rates (G) for Torres Strait geomorphic zones and corresponding reef zones defined by Kinsey and Hopley (1991) for the GBR

Geomorphic zones defined for Torres Strait	Reef zones (Kinsey and Hopley, 1991)	G (kgCaCO₃m⁻²yr⁻¹)
Forereef	Hard coral/algal substratum	10
Reef crest Coralgal Flat	Algal pavement/ active reef flats	4
Patch Lagoon and patches Deep lagoon Sanded backreef	Deep reef shoals/shallow lagoon with patch reefs	2
Sanded reef flat	Sand and rubble flats	0.5

Average coverage of carbonate producing organisms, in combination with published growth data, were used to extrapolate average productivity rates for each zone (Leon, 2010). Sanded reef flats, such as the sand apron covering the emergent flat on Warraber reef, are mostly composed of secondary CaCO₃ producers such as foraminifera, molluscs and gastropods. A value of 0.5 G, comparable to the value reported by Yamanao et al. (2000) for similar environments, was assigned to these zones. Submerged geomorphic zones devoid of extensive coral cover, such as the sanded backreef of Bet reef, or lagoonal environments with sparse coral patches, were assigned a value of 2 G. Reef flats with extensive coral and algae coverage, such as the productive submerged reef flats in the leeward of Warraber, were assigned a value of 4G. Similarly, reef crests covered by a combination of coral rubble and encrusting coralline algae, such as the reef crest at Warraber reef, were assigned a value of 4 G. Finally, given the average coral coverage on forereef zones across Torres Strait varies between 60-80%, as derived from the surveys by Long et al. (1997) and Skewes (1997), a value of 10 G was assigned to forereef zones, similarly to the regional census-based value for forereef zones reported by Vescei (2001). Table 3 shows the generalized average productivity rates for the different intra-reef geomorphic zones in Torres Strait compared to rates derived by Kinsey and Hopley (1991) for reef zones in the GBR.

Scaling-up gross CaCO₃ production

Kinsey and Hopley (1991) derived weighted averages of gross CaCO₃ production rates for each reef type in the GBR based on the proportion of intra-reef zones and associated G values (Fig. 4). CaCO₃ production across the region was estimated using these weighted

rates and the average sizes for each reef type. This approach was extended to scale-up gross CaCO_3 production for Torres Strait reefs.

The generalized gross productivity rates associated with geomorphic zones in Torres Strait (Table 3) were used and the proportion of geomorphic zones for each classified reef type was calculated. Weighted G values for each reef type were derived based on these proportions. Finally, the average size of reef types and associated weighted averages of gross CaCO_3 production rates were used to extrapolate gross production across Torres Strait.

For comparative purposes, the proportional composition of mapped geomorphic zones and associated gross CaCO_3 production rates for each reef type in Torres Strait, as derived in this study, were compared with the composition of reef types in the GBR, as derived by Kinsey and Hopley (1991). Due to differences in base datasets and mapping methods, typical reef types in the GBR were characterised applying the methods proposed in this study. Examples of the reef types were chosen following descriptions by Hopley et al. (2007) and geomorphic zones were classified using Landsat ETM+ satellite imagery, except where indicated, as described in Leon and Woodroffe (2011). The following reefs were classified: 1) Potter reef as a crescentic reef type, 2) Heron reef as a lagoonal reef type (data from Phinn et al. (2012)), 3) Wheeler reef as a planar reef type, 4) Lizard island as a fringing reef type (data from Hamylton et al. (Accepted January 2013)) and 5) Yonge reef as a ribbon reef type.

4 Results

4.1 Classification of reef types

A total of 606 reefs, adding to approximately 2,423 km^2 of surface area, were mapped and classified in Torres Strait. Fig. 6 shows the best classification tree describing reef types across Torres Strait. The tree was chosen due to a relatively high Kappa coefficient of 82.6%, relatively low percentage of incorrectly classified instances (10.2%) and a small size (21) and number of leaves (11). Reef types were best described by a combination of the proportion of mapped geomorphic zones together with three proxies for physical variables: trend of seabed depth (proxy for depth to Pleistocene foundation), longitude (proxy for cross-shelf variation) and the minimum multidirection exposure index (proxy for wave exposure).

Description of Torres Strait reef types derived from the machine-learning classification were consistent with Hopley's description of reef types for the GBR. The main

features distinguishing reef types in Torres Strait were the proportion of corallal flat zone, proportion of reef crest zone and the trend of seabed depth (top nodes in Fig. 6). Table 4 shows the proportion of intra-reef geomorphic zones and proxy values for the physical variables incorporated in the classification tree. The results indicate that ribbon reefs have a small proportion of reef crest zones and rise from relatively deeper water depths. Juvenile patch and submerged reefs show smaller proportions of corallal flats, as opposed to the more mature reef types. Generally, crescentic reefs have relatively well-defined reef crests and are exposed to less wave energy, as suggested by smaller values of the minimum multidirectional wave exposure index. Conversely, lagoonal reefs are often exposed to comparatively higher wave energy, but those with lower wave energy have less developed reef crests. Towards the centre of the analysed area, small vegetated cays were found on lagoonal reefs and larger ones on planar reefs. On the westernmost area, planar reefs were discriminated from crescentic reefs by exposure to relatively higher wave energy. Finally, fringing reefs are shown to be adjacent to hard substrates such as granitic or volcanic islands.

Table 5 shows the average dimensions and total area for classified reef types in Torres Strait. Approximately half of the classified reefs are patch reefs which have the smallest mean area (0.4 km^2) and cover 5% of the $\sim 2,400 \text{ km}^2$ mapped region. Crescentic and lagoonal reefs are the most extensive types, with average dimensions reaching 26.7 km^2 and 4.5 km^2 , respectively. Ribbon reefs are relatively frequent (12%) but have smaller dimensions on average (2 km^2), hence covering only 6% of the total mapped area. Planar and fringing reef types have similar average maximum dimensions (29 km^2) but fringing reefs are less common on the mapped region. It is worth mentioning, though, that several fringing reefs in Torres Strait are located towards the west of the Landsat image coverage and were not mapped in this study.

4.2 Gross CaCO_3 production per reef type

The estimated gross CaCO_3 production rates (G) derived from the generalized census-based method were comparable to published values estimated using hydrochemical methods across different geographic regions at both whole-reef and intra-reef scales. The estimated gross production rate of 1.81 G for the complete Warraber reef platform is close to the weighted average of 1.9 G value assigned for planar reefs in the GBR by Kinsey and Hopley (1991). Similarly, the estimated rate of 3.14 G for the complete Bet reef platform is close to the weighted average of 3 G estimated for lagoonal reefs in the GBR by Kinsey and Hopley

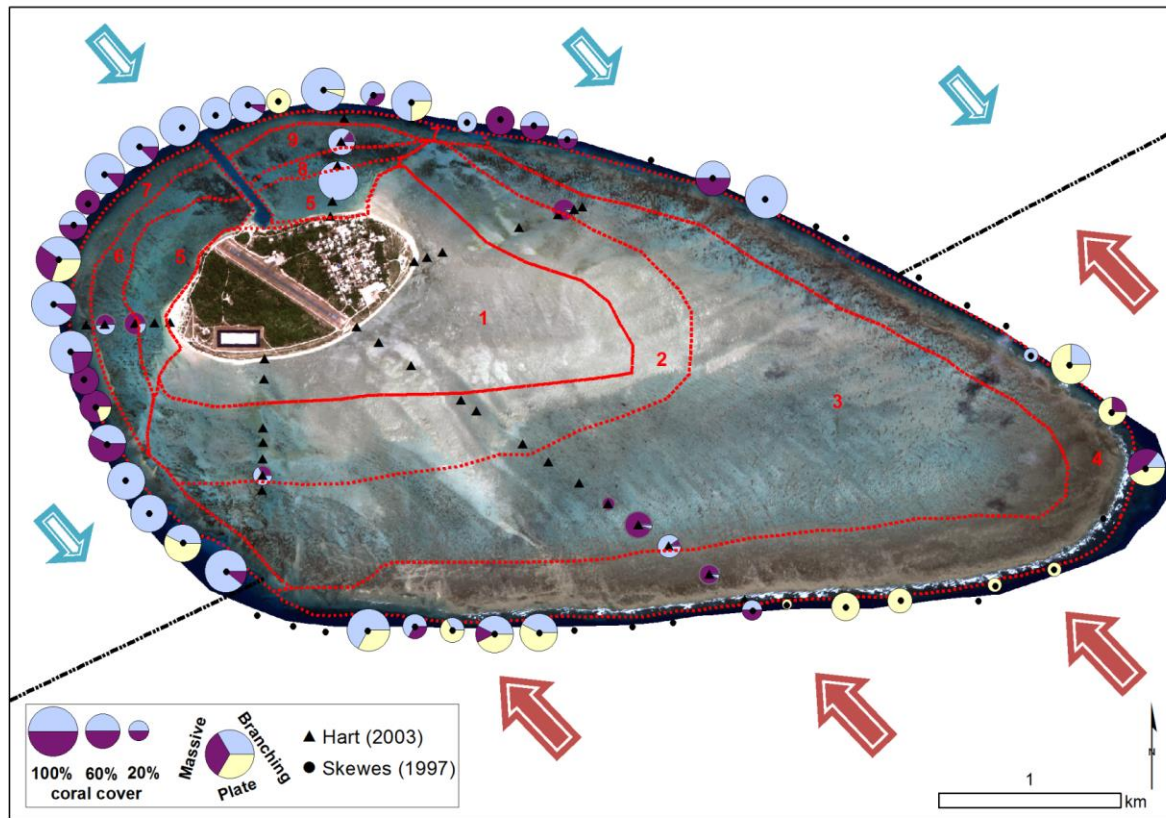


Fig. 6: Classification tree best describing reef types across Torres Strait based on proportional coverage of intra-reef geomorphic zones and physical variables (trend of seabed depth, average longitudinal position and minimum multidirectional wave exposure).

(1991). These results provide an independent means of validation of one method against other and suggest that rates of production are comparable across regions.

The proportion of geomorphic zones and associated average CaCO_3 production rates (G) within reef types in Torres Strait, determined in this study, and those in the GBR, as derived by Kinsey and Hopley (1991), were also shown to be comparable (Fig. 7). Trends in composition between reef types are similar with the exception of planar and fringing reef types. Overall, there is an overestimation of mapped geomorphic zones with associated higher G values by the proposed methods and datasets in this study, as opposed to the methods and datasets used by Kinsey and Hopley (1991). This is evidenced in the trends resulting from applying the methods proposed in this study to selected reef types in the GBR, particularly for planar and fringing reef types (Fig. 7).

The weighted gross CaCO_3 production rate for each classified reef type in Torres Strait was derived from the proportion of intra-reef geomorphic zones within each reef type (Table 5). Weighted values ranged from a minimum 2 G for patch reef types, to ~3.3G for

Table 4: Proportion of geomorphic zones per each reef type across Torres Strait and physical proxies used for classification

	Reef type	Patches	Crescentic	Lagoonal	Planar	Ribbon	Fringing
Proportion of geomorphic zones within reef types (%)	Forereef	0	9	14	17	12	10
	Reef crest	0	25	16	32	22	28
	Coralgal flat	0	11	23	35	31	16
	Sanded reef flat	0	6	3	10	1	9
	Sanded backreef	0	22	23	1	8	4
	Lagoon and patches	0	16	19	0	27	1
	Deep lagoon	0	6	2	0	0	0
	Patch	100	0	0	0	0	0
	Seagrass	0	5	0	0	0	0
	Unvegetated island	0	0	0	0	0	16
	Vegetated island	0	0	0	4	0	16
Physical proxies	Minimum multifetch exposure index	0.0008	0.0001	0.0004	0.0008	0.0001	0.0006
	Average X coordinate (UTM 54S)	810323	776033	784420	730042	826091	727354
	Average depth from global bathymetric trend (m)	-63	-27	-28	-21	-133	-21

crescentic and lagoonal reefs, to over 4 G for planar, ribbon and fringing reefs. The highest weighted G values are mainly related to larger mapped areas of highly productive geomorphic zones such as forereef areas, reef crests and coralgal zones. Conversely, lower values are related to larger mapped areas of less productive submerged backreef and lagoonal geomorphic zones.

The classified reefs across the Torres Strait region were estimated to produce a total amount of 8.7 million tonnes of CaCO_3 per year, at an average rate of 3.7 G, based on the weighted G values and average dimensions for each reef type (Table 5). This is a higher rate than the 2.3 G estimated for the GBR by Kinsey and Hopley (1991), despite GBR reefs being more densely distributed than those mapped in Torres Strait (9% and 7% of studied areas, respectively). A considerable proportion of the total estimated gross production is attributed to extensive crescentic reefs such as the Warrior reefs (194 km²) or the approximately 350 km² covered by the lagoonal Cumberland Reefs complex. Crescentic and lagoonal reef types make up 36 and 39% of the total estimated production, respectively. Reef types with higher weighted G values, such as planar, ribbon or fringing types, do not significantly contribute to the total production estimate due to their overall average smaller dimensions. Planar reefs such as Warraber, Poll or Yorke platforms (Fig. 1) extend on average for less than 5 km², contributing to about 12% of the total estimated production. Similarly, ribbon reefs to the

500 Table 5: Summary statistics for each reef type across Torres Strait with associated gross CaCO₃ productivity per geomorphic
501 zone and weighted average gross CaCO₃ productivity.

Reef type	Count	Minimum area (km ²)	Maximum area (km ²)	Mean area (km ²)	Total reef area (km ²)	% in each calcification	
						G=10	G=4
Patches	329	0.01	8	0.4	129	0	0
Crescentic	36	0.9	194	26.7	961	9	36
Lagoonal	124	0.03	66	7.5	928	14	40
Planar	46	0.3	29	4.5	209	17	70
Ribbon	62	0.01	9	2.2	137	12	53
Fringing	9	1.0	29	6.5	59	15	65
TOTAL	606				2,423		

east of the shelf have an average area of approximately 2 km² and only contribute approximately 7% of the total gross production.

5 Discussion

Mapping of coral reef geomorphology has been traditionally undertaken based on the interpretation of optical remotely sensed imagery. This is possible because of the co-occurrence of similar ecological and geomorphic zones which is related to the adaptation strategies corals have developed to local gradients in hydrodynamics and light availability (Done, 1982). This geomorphic or eco-geomorphological zonation is generally well-defined where high gradients in wave energy are present (Chappell, 1980). Geomorphic zones appear to be very similar across regions although coral assemblages are highly variable within and between reefs (Blanchon, 2011).

The accuracy of coral reef geomorphic mapping based on optical imagery has been limited by the spatial and spectral resolution of remote sensors (Brock et al., 2006; Mumby and Edwards, 2002), despite recent advances in image classification techniques (Leon and Woodroffe, 2011; Phinn et al., 2012). For example, the differences between the proportions of geomorphic zones in planar and fringing reefs of Torres Strait and the GBR are mainly due to characteristics of the underlying imagery. The coarser spatial resolution of Landsat ETM+ imagery (30 m) does not allow an efficient discrimination between live coral/algae coverage and sandy or rubble areas, as opposed to the higher spatial resolution of aerial photography used by Kinsey and Hopley (1991) in their analysis.

Classification techniques incorporating image analysis together with high-resolution bathymetric datasets and terrain derivatives have shown potential to improve the accuracy and precision of mapping reef landforms (e.g. Leon et al., 2012; Zieger et al., 2009). However, the complex maze of submerged and very shallow intertidal platforms of reef systems, such as Torres Strait, still pose considerable logistical challenges for the acquisition of detailed bathymetric datasets even with the advent of technologies such as bathymetric LiDAR (Klema, 2011). The novel method proposed in this study to characterise the geomorphology of reef types based on classification trees provides an objective and repeatable data-driven approach that can be applied to different regions. The method is flexible and can accommodate different classification schemes and geospatial datasets, as these become available or updated.

The classification scheme for reef types based on Hopley's model was chosen in this study due to the morphological similarities between reefs in Torres Strait and the GBR. Despite the complexity of the maze of reefs in Torres Strait, there are broad regional trends, for example the continuation of the ribbon reefs northward from the GBR along the exposed outer margin. The distribution of these reefs is underpinned by similar geological processes, sea-level history in the Holocene and exposure to the same wind/wave energetic regime, resulting in comparable geomorphic zonation. However, the influence of the Fly River and the strong tidal currents flowing through Torres Strait, which are capable of producing tidally incised shelf valley systems where reef grows, are environmental processes that also exert a control on morphology (Harris et al., 2005).

Previous studies have shown remarkable consistency in the size and shape dimensions of reef platforms across different coral reef regions (Andréfouët et al., 2006; Phinn et al., 2012; Purkis et al., 2007). Characteristics of reef types in Torres Strait and the GBR are comparable but the relatively shallow and narrow dimensions of the shelf on Torres Strait influence the local geomorphology and spatial distribution of reef platforms. For example, the average sizes of crescentic and planar reef types are similar across both regions. Crescentic reefs, exemplified in Torres Strait by the massive Warrior Reefs, are also the largest reef type on both regions. On the contrary, trends in the spatial distribution of reef types differ across the regions.

Hopley et al. (2007) showed that the distribution of lagoonal and planar reefs in the GBR is constrained by latitudinal extent. Most lagoonal and planar reefs are clustered in the outer lagoon of the southern section of the GBR (south of 19°). A second cluster of planar reefs is also observed in the northern section of the GBR (north of 16°). Hopley et al. (2007)

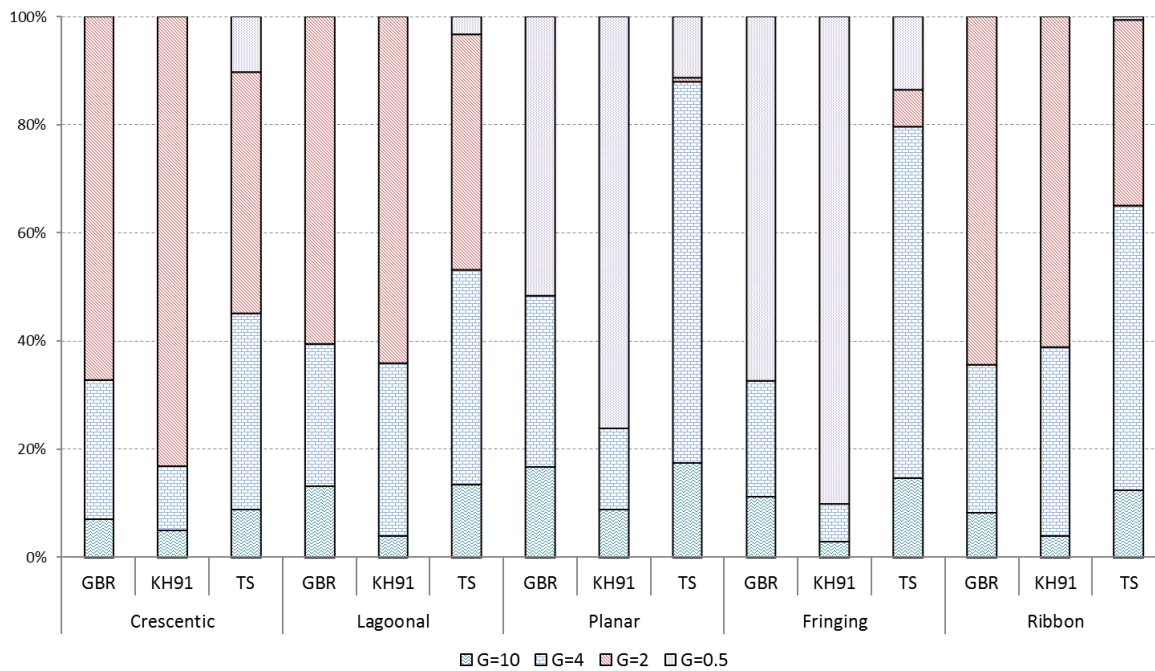


Fig 7: Comparison between proportions of mapped geomorphic zones and associated gross CaCO_3 production rates (G) between reef types in the GBR, as derived by Kinsey and Hopley (1991) methods (KH91), and Torres Strait (TS) and selected reef types in the GBR (GBR), as derived by methods from this study.

suggested that this distribution was correlated with reef size, as smaller reefs infill faster. In Torres Strait, classified lagoonal and planar reef types follow a clear cross-shelf distribution. Lagoonal reefs are distributed towards the centre (east of 143.5°) of the region, while planar reefs are observed towards the west of the studied area. However, the size distribution of lagoonal reefs varies widely and no evidence appears to exist supporting the correlation between size and types of reef amongst classified reefs in Torres Strait.

In terms of CaCO_3 production, the approach employed in this study was to scale-up gross CaCO_3 production based on geomorphic zones; this potentially bridges a gap between local and regional studies of reef systems and provides a basis to investigate reef evolution and better manage these fragile and complex systems. As noted by Hopley et al. 2007, this is particularly relevant within a context of rapidly changing climate, as present morphology will significantly influence future morphology and the characteristics of reef habitats. For example, recent work undertaken by Hamylton et al. (Accepted January 2013) showed the potential of modelling reef evolution considering projected sea-level rise scenarios and census-based CaCO_3 production rates related to benthic coverage and geomorphic zones.

Published rates of CaCO_3 productivity values based on hydrochemistry studies were independently verified and complemented using a regional census-based approach for

different reef types across Torres Strait. Extrapolated production rates based on detailed and regional census-based approaches for geomorphic zones across Torres Strait were very similar and comparable to those reported elsewhere, particularly values for the GBR based on alkalinity-reduction methods. However, comparisons between total CaCO_3 productivity across regions should be treated carefully as the higher rate of gross CaCO_3 productivity estimated for Torres Strait actually reflects the greater proportion of mapped geomorphic zones with associated high productivity rates. Moreover, the employed regional census-based approach is subject to uncertainties in data and methods and warrants further research. It may be necessary to update and refine these values in the context of reduced calcification due to global trends in coral reef ecological decline (De'ath et al., 2009; De'ath et al., 2012) and increased ocean acidification and sea surface temperatures (Kleypas and Yates, 2009; Silverman et al., 2009).

Regional or global carbonate budgets can help managers by complementing ecological assessments of reef state (Perry et al., 2012; Vecsei, 2004). This can provide insights into processes underlying reef evolution and associated sedimentary landform dynamics, such as reef island growth or erosion, as environmental conditions change. This is very relevant in the present context of reef island stability and the increased decline of coral coverage due to combined effects of factors such as tropical cyclones, coral predation by crown-of-thorns starfish and human-induced coral bleaching and reduced calcification due to increased ocean acidification and sea-surface temperatures.

Advances in the classification of reef geomorphology, such as those proposed in this study, combined with regional census-based approaches based on rapid ecological assessments have the potential to be adapted and transferred to different coral reef regions, depicting a more accurate picture of interactions between reef ecology and geomorphology.

6 Conclusions

This paper has presented a detailed morphological characterization of coral reefs in Torres Strait and a novel approach to classify reef types in Torres Strait based on objective and repeatable rule-inductive classification algorithms. CaCO_3 gross productivity rates were assigned to mapped geomorphic zones within each reef type. Published rates of CaCO_3 productivity values based on hydrochemistry studies were independently verified and complemented using a regional census-based approach for different reef types across Torres

Strait. CaCO_3 gross productivity was subsequently scaled-up across the region extending the methods proposed by Kinsey and Hopley (1991).

Results suggested that reefs in Torres Strait share morphological similarities with those on the GBR but local geomorphology is modified by the narrow and shallow dimensions of the Strait and the strong tidal currents flowing across it. Overall, the scaling-up approach employed in this study bridges a gap between detailed and regional studies of reef systems and provides a basis to better manage these fragile and complex systems.

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